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Effect of Parameters on the Runoff Erosion Control Performance of Structurally Modified Jute and Coir Geomeshes over Loamy Sand

Vpliv parametrov na površinsko spiranje ilovnatopeščene površine s pomočjo strukturno modificiranih geomrež iz jutnih in kokosovih vlaken

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Abstract

Soil erosion is a serious environmental problem that can be controlled using bioengineering techniques. In using a bioengineering technique, temporary reinforcement is performed with geomeshes until vegetation takes root. In this study, structurally modified jute and coir geomeshes were tested for runoff erosion control and runoff volume over loamy sand at different slope angles. The laboratory results revealed that all parameters (slope angle, type of weave and type of material) had a significant effect on the erosion control performance of geomeshes. The slope angle contributed most (52.34%) to runoff erosion control, followed by weave type (25.79%) and type of material (12.28%). At lower and medium slope angles (of 15o and 30o, respectively) the twill-woven structure of coir geomeshes provided better erosion control than plain- and satin-woven structures, while plain-woven jute geomeshes demonstrated better erosion control at all slope angles. To understand the overall impact, a germination test was also conducted. According to the germination test results, the twill weave of jute geomeshes provided the highest rooting length. In general, plain-woven jute geomeshes are preferred for better erosion control on a high slope angle, while plain and twill can be used on a low slope angle.
Keywords: soil erosion, runoff erosion, geomeshes, natural fibre, loamy sand, jute, coir, germination

Izvleček

Erozija tal je resen okoljski problem, ki ga je mogoče nadzorovati z bioinženirskimi tehnikami. Pri tem z geomrežami prehodno ojačijo tla, dokler se ne vzpostavi vegetacija. V raziskavi so bile proučevane strukturno modificirane geomreže iz jutnih in kokosovih vlaken, namenjene zaščiti tal pred erozijo zaradi spiranja ilovnatega peska. Laboratorijski rezultati so pokazali, da vsi proučevani parametri, tj. kot naklona tal, tkalska vezava geomrež in njihova surovinska sestava, pomembno vplivajo na učinkovitost nadzora erozije. Na erozijo najbolj vpliva kot naklona (52,34 %), sledita vrsta tkalske vezave (25,79 %) in vrsta vlaken (12,28 %). Pri najmanjšem in srednjem kotu naklona (15°, 30°) je geomreža iz kokosovih vlaken v vezavi keper zagotovila boljši nadzor nad erozijo od geomrež v vezavah platno in atlas. Geomreža iz jutnih vlaken v vezavi platno pa je pokazala najboljši nadzor nad erozijo pri vseh kotih naklona. Za poznavanje celovitega učinka je bil izveden test kalitve semen. Ugotovljeno je bilo, da geomreže iz jutnih vlaken omogočajo največjo dolžino

korenin. Geomreža iz jutnih vlaken v vezavi platno zagotavlja boljši nadzor nad erozijo pri velikih naklonih terena, za majhen naklon terena pa so primernejše geomreže v vezavah platno in keper.
Ključne besede: erozija tal, erozija odtokov, geomreža, naravno vlakno, ilovnat pesek, juta, kokos, kalitev

1 Introduction

Soil is the unconsolidated material sediments and solid particle deposits of disintegrate rocks. The process of the transportation and detachment of top soil along with other organic materials by wind, water and human activity is known as 'soil erosion' [1–3]. This has been the most prevailing problem since the 1930s and, after the 90 years of research, it is still a major concern of researchers. In the last few decades, the global rate of erosion has been exceeding new soil formation by 10 to 20 times. It is the second most pressing environmental problem throughout the world's terrestrial ecosystem, after population growth. According to a report by the World Health Organization, more than 3.7 billion people are malnourished in the world due to the loss of cropland as the result of soil erosion [4]. At present, around 80% of the world's agricultural land suffers moderate to severe erosion, while 10% of that land experiences slight erosion. As the result of soil erosion, about 30% of the world's plowable land has become unproductive and has been abandoned for agricultural use during the last 40 years [4–5]. The United States is losing soil 10 times faster, while China and India are losing soil 30 to 40 times faster than the natural replenishment rate. About 3,280,000 km2 of land (i.e. 53% of the total land area of the country) is prone to the soil erosion in India. About 29% of total eroded soil is permanently lost to the sea, 10% is deposited in reservoirs resulting in the loss of storage capacity by 1–2% annually, and 61% of eroded soil is being transported from one place to another. Given the seriousness of the soil erosion problem, integrated soil erosion control measures are needed. It has been said that the economics of the situation strongly suggest that soil erosion control is a better policy than sediment removal, as controlling erosion is only 1/15 as expensive as sediment removal. The cost-benefit ratio between erosion control removal is 5.2:1 [4, 7].
The main types of erosion are runoff erosion, interrill, rill, gully and streambank erosion. Among the various types of erosion, runoff erosion induced by runoff rainwater is the most common and results in various minor to major problems. It leads to the loss of soil structure and other organic matter in the soil, along with other devastating problems, such as landslides, floods and desertification [8]. Moreover, it reduces soil stability, which is an important factor for the construction of roads, embankments, underlays at hill slopes and seashores. The control of soil erosion is important from environmental and engineering aspects. This can be achieved through a proper soil management system or bioengineering techniques [9–10]. Bioengineering techniques use natural vegetation and geotextile materials/Rolled Erosion Control Products (RECPs) to address geotechnical problems. RECPs used in erosion control applications provide temporary support to the soil until permanent vegetation takes root. Hence, open weave RECPs made of natural fibres, such as like coir and jute, are highly preferred in runoff erosion control applications on hill slopes and disturbed lands [11–12]. The biodegradability of natural RECPs nourishes rooted vegetation with nutrients and offers a sustainable solution to control soil erosion and land degradation [13]. According to previous findings, plain-woven coir geomeshes demonstrate 40–60% erosion control, while jute geomeshes demonstrate 70-80% erosion control [13, 14]. It is well known that commercially available, plain-woven RECPs effectively mitigate runoff erosion. However, limited studies are available regarding the performance of structurally modified jute and coir geomeshes, at lower, medium and higher slope angles.

2 Materials and methods

2.1 Materials

For this study, different jute and coir geomeshes were taken, as shown in Table 1. Jute and coir geomeshes were prepared with an average mesh opening size of 19 x 19 mm and 10 x 12 mm according to commercially available geomeshes. The structure of the geomeshes was changed taking into account a previous study [14].
Full factorial design was used to identify the effect of three independent factors, i.e. type of material, slope angle and type of weave, on erosion control percentages, as shown in Table 2.
The performance of jute and coir geomeshes was studied for soil erosion control using soil from Hoshiarpur (foothills of the Himalayas). Hoshiarpur

Table 1: Properties of jute and coir geomeshes

Material	Type of weave	Linear density (tex)	Diameter (mm)	Mesh opening size (mm)	Weight per unit area (g/m^2)	Flexural rigidity (μNm)			
						Dry		Wet	
						Warp	Weft	Warp	Weft
Jute	Plain	4724	3.9	10 x 12	541.7	1289	989	540	313
	Twill	4724	3.9	10 x 12	541.7	828	634	289	125
	Satin	4724	3.9	10 x 12	541.7	324	227	162	65
Coir	Plain	5090	4.5	19 x 21	580	5753	2877	2034	1423
	Twill	5090	4.5	19 x 21	580	4763	2316	1578	1137
	Satin	5090	4.5	19 x 21	580	3862	1673	732	345

Table 2: Full factorial design

Sr no.	Type of material	Slope angle (°)	Type of weave
1	Jute	15	Plain
2	Coir	30	Twill
3		45	4 end satin

lies at an altitude of 296m and a latitude between 31.51° N and 75.91°. The soil texture was observed through sieve analysis based on IS:2720, and contains 85% sand, 10% silt and 5% clay [15].

2.2 Runoff erosion test

A runoff erosion control test was carried out according to the ASTM D 7101 standard, with some modifications in ramp size (Figure 1 (a)) [16]. According to previous studies, a ramp size of 50 cm length and 25 cm width was used. V jet nozzles were used to simulate rainfall of 100 mm/h for three minutes during each trial. Runoff erosion tests were carried out with soil (soil-infiltration conditions) and without soil (zero-infiltration conditions) to better understand the interaction between soil and geomesh (Figure 1(b) and Figure 1(c)). Under soil-infiltration conditions, soil from the Hoshiarpur region was placed in a soil tray measuring

a) b) c)

Figure 1: Runoff erosion test at different infiltration conditions: a) runoff erosion set-up, b) soil-infiltration conditions, c) zero-infiltration conditions

50 cm in length, 25 cm in width and 25 cm in depth. Based on the ASTM D 698 standard, soils were compacted in the test tray at 16% moisture content by dropping a 5.50lbf rammer from a height of 30 cm. The prepared soil tray was covered with geomesh and placed at different slope angles on the instrument and subjected to rainfall. Rainfall was simulated for three minutes for each sample, while runoff water with eroded soil was collected using the sedimentation method. The first three tests were not considered in the calculation in order to avoid errors that may occur due to the initial absorption of the water in the soil and geomeshes. Similarly, testing was also performed for uncovered soil trays (without geomeshes) to evaluate control test performance. Erosion control percentages can be calculated using the equation 1:

$$Erosion\ control\ (\%) = \frac{E - C}{E} \quad (1)$$

where, *E* represents eroded soil without geomesh (g) and *C* represent eroded soil with geomesh (g).

Under soil-infiltration conditions, water was absorbed by the soil, which hinders the intended role of geomeshes. To understand the overall effect of geomeshes, a runoff erosion test was carried out under zero-infiltration conditions (without soil). Under zero-infiltration conditions, geomeshes were laid on a smooth surface and subjected to rainfall for three minutes to collect runoff water. Rainfall was then halted for three minutes to collect culmination discharge. Due to the moisture-retaining capacity and storage effect of geomeshes, water continued to drain even after rainfall was stopped. This culmination volume provided the overall runoff erosion performance of geomeshes at different slope angles.

2.3 Germination test

A germination test was performed in accordance with the ASTM D 7322 standard, according to which, earthen pots were filled with different soil and sown with an equal number of wheat seeds (60 seeds/pot). Each soil was covered with the different structures of geomeshes, while one was left uncovered. These pots were kept at a uniform temperature, lighting conditions and 30–35% humidity for 21 days. Two trials of germination tests were conducted to ensure the reliability of test results. At the end of 21 days, the percentage of vegetation was calculated using equation 2:

$$Vegetation\ (\%) = \frac{Number\ of\ plants\ germinated\ in\ the\ pot\ with\ geomesh}{Number\ of\ plants\ germinated\ in\ the\ pot\ without\ geomesh} \quad (2)$$

The number of roots, length of roots and total rooting were the important factors that determine the soil stability and germination of plants. After 21 days, 10 plants were randomly uprooted, and the average primary root length and average number of roots per plant were measured in each pot [14]. Total rooting length after 21 days was calculated using equation 3.

$$Total\ rooting\ length = N \times n \times L \quad (3)$$

where, *N* represents the total number of plants after 21 days, n represents the average number of roots per plant and *L* represents the average primary root length (cm).

3 Result and discussion

Structurally modified (plain, twill and satin) jute and coir geomeshes were placed at different slope angles (15°, 30° and 45°) to identify runoff erosion control percentages and runoff volume under soil-infiltration conditions (with soil). The performance of different jute and coir geomeshes is presented in Table 3.

3.1 Runoff erosion control performance of jute and coir geomeshes under soil-infiltration conditions

Figure 2 shows the effect of structurally modified jute and coir geomeshes at a 15° slope angle. Twill-woven coir geomeshes demonstrated the highest erosion control percentage (59.1%), while plain and satin demonstrated erosion control percentages of 47.5% and 39.9%, respectively.

It is evident from Figure 2 that erosion control percentage increases when the plain-woven structure of the geomeshes was altered to twill-woven geomeshes and decreases when altered to a satin-woven structure. Coir fibre contains 35–45% lignin, which leads to higher flexural rigidity in the plain-woven structure (Table 1) [17–18]. For this reason, coir geomeshes demonstrated less contact with the soil, resulting in lower erosion control. As the structure of the geomesh is changed from plain to twill, float length at the back side of geomesh increases, which results in lower flexural rigidity. The flexural rigidity of the geomeshes was decreased from 2877 μNm to 2316 μNm

Table 3: Runoff erosion control performance of jute and coir geomeshes at different slope angle

Type of material	Type of weave	Runoff volume (ml)			Soil erosion control (%)		
		Slope angle (°)					
		15	30	45	15	30	45
Coir	Plain	483	492	501	47.5	39.8	32.1
	Twill	442	456	519	59.1	52.8	24.2
	4 end satin	499	534	561	39.9	23.5	11.9
Jute	Plain	289	328	349	73.1	64.9	45.2
	Twill	299	362	372	62.1	55.9	29.5
	4 end satin	315	381	394	52.2	44.2	14.8

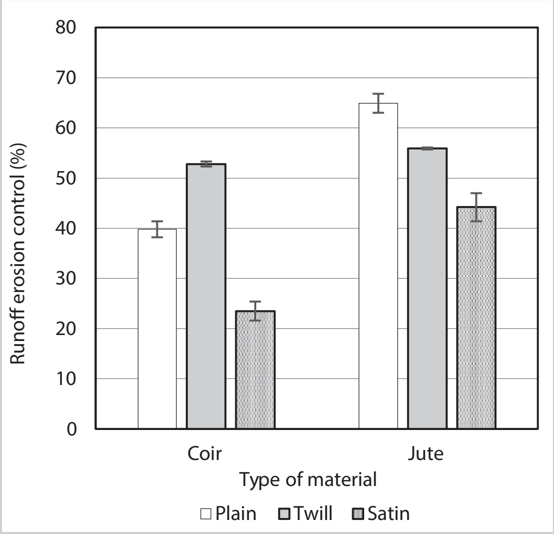


Figure 2: Runoff erosion control performance of structurally modified jute and coir geomeshes at a 15° slope angle

by changing the structure. The satin-woven structure demonstrated the lowest erosion control due to the lowest flexural rigidity because its structure becomes disturbed and increases the area for the direct impact of rain. Another reason for the lower erosion control is the higher erodibility of the soil [14–15]. Loamy sand contains 85% sand, 10% silt and 5% clay, which starts to erode in a short span of time and exerts pressure on the weft. For this reason, structure the of the coir geomeshes becomes disturbed and a greater area of soil is exposed to the rainfall. Error bars confirm that there is a significant difference in erosion control performance of the different woven structures of the jute and coir geomeshes. In contrast to coir geomeshes, plain-woven jute geomeshes demonstrated better erosion control on loamy sand. Plain-woven geomeshes demonstrated the highest erosion control percentage (73.1%), followed by twill and satin at 62.1% and 52.2%, respectively. This is because jute has a lower amount of lignin, which results in lower flexural rigidity [19–20] (Table 1). Moreover, with change in its structure, its flexural rigidity significantly decreases up to 227 μNm. For this reason, twill and satin-woven structures of geomeshes cannot withstand the water flowing velocity, resulting in lower erosion control. Analysis of variance shows that the type of weave has a significant effect on the erosion control performance of geomeshes. The type of weave contributes 24.85% to the erosion control performance of geomeshes (Table 4).

Coir and jute geomeshes demonstrated a similar trend at a 30° slope angle (Figure 3). At a 45° slope angle, the plain-woven structure of jute and coir geomeshes demonstrated better erosion control. At a higher slope angle, the velocity of the flowing water increased, which decreased the cohesion between the soil particles and led to the easy transportation of the soil particles. Under similar conditions, lower erosion control was observed at a higher slope angle (Figure 4) [21–22].

ANOVA also confirmed that the slope angle influenced the erosion control performance of jute and coir geomeshes, and contributed the most (52.41%) to the total (Table 4).

In general, jute geomeshes demonstrated better erosion control than coir geomeshes. This is due to their higher moisture absorption and lower flexural rigidity. For this reason, jute geomeshes demonstrated better drape with soil and thus followed the contours over the soil surface for better erosion control [23]. In

Table 4: ANOVA of the runoff erosion control performance of jute and coir geomeshes

Effect	Contribution (%)	SS	Degree of freedom	MS	F-ratio	p-value
Weave	24.85	1292.70	2	646.35	24.209	0.000
Slope angle	52.41	2725.66	2	1362.83	51.044	0.000
Type of material	13.18	685.73	1	685.73	25.684	0.000
Weave * Type of material	4.40	229.13	2	114.57	4.291	0.045
Error	5.13	266.99	10			
Total	100	5200.21				

contrast to jute geomeshes, coir geomeshes demonstrated high flexural rigidity, which made it difficult for them to follow the contours of the soil and control erosion. The type of material also had a significant influence on the erosion control performance of geomeshes, and contributed 13.18 % to runoff erosion control. The type of material and weave had a significant interaction effect and contributed 5.13% to the total (Table 4).

3.2 Runoff erosion control performance of jute and coir geomeshes under zero-infiltration conditions

Table 5 shows the performance of modified jute and coir geomeshes under zero-infiltration conditions (without soil). Coir geomeshes demonstrated higher runoff than jute geomeshes due to the stiffer protruding fibres on its surface. These protruding fibres reduced the contact between coir geomesh and metallic ramp, as shown in figure 5(a), while jute geomeshes draped well with the metallic surface (Figure 5 b). Hence, a lower runoff was observed in jute geomeshes.

Similarly, jute geomeshes also outperformed coir geomeshes in culmination discharge. Culmination discharge depends upon the water absorption and storage effect of the geomeshes. Jute geomeshes have a higher water absorption capacity than coir [24]. Due to this quality, culmination discharge is higher in jute than coir geomeshes. In can also be inferred from Table 5 that the slope angle also affects the runoff volume and culmination discharge. It was observed that runoff volume decreased as the weave was changed in both type of geomeshes. This is because the weaves reduced the flexural rigidity of the geomeshes. The runoff volume and culmination discharge of jute and

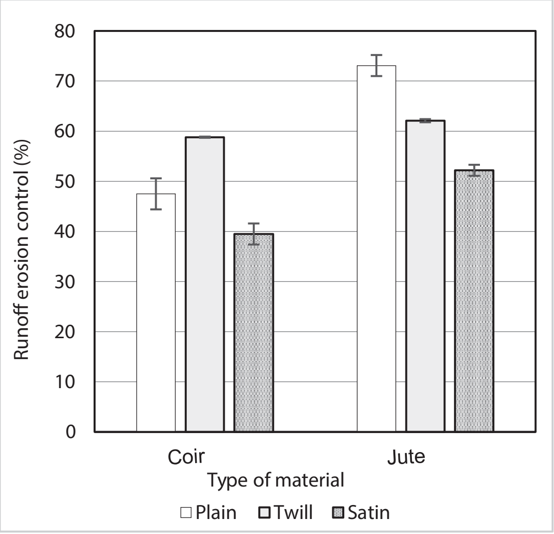


Figure 3: Runoff erosion control performance of structurally modified jute and coir geomeshes at a 30° slope angle

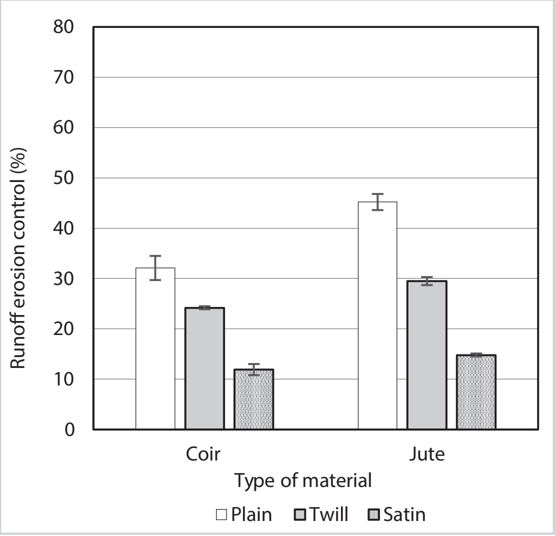
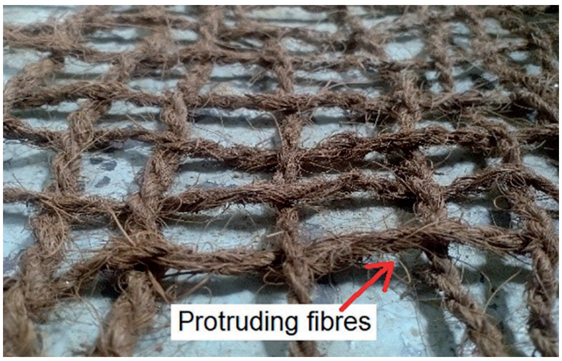


Figure 4: Runoff erosion control performance of structurally modified jute and coir geomeshes at a 45° slope angle

Table 5: Runoff volume and culmination discharge under zero-infiltration conditions

Type of geomeshes	Slope angle (°)	Runoff volume (ml)			Culmination discharge (ml)		
		Plain	Twill	Four end satin	Plain	Twill	Four end satin
Jute	15°	385	322	304	162	168	174
	30°	396	360	345	171	180	206
	45°	415	376	365	184	196	s10
Coir	15°	571	555	543	42	43	44
	30°	584	560	549	48	53	55
	45°	602	595	578	49	56	59



a)

b)

Figure 5: Geomeshes under zero-infiltration conditions: a) coir geomeshes b) Jute geomeshes

coir geomeshes under zero-infiltration conditions at different slope angles followed the same trends as observed under soil-infiltration conditions, while the culmination discharge of coir geomeshes at different angles and different weaves increased. However, no significant differences were observed.

3.3 Germination test

Figure 6 shows germination results after 21 days for jute and coir geomeshes. Table 6 shows the germination pattern of different woven jute and coir structures over loamy sand soil. At the end of third day, 19, 24 and 28 plants were germinated in plain, twill and satin respectively. The satin-woven structure demonstrated the highest initial vegetation growth because of its higher float length than the other structures.
A higher float length decreased the flexural rigidity of the geomeshes. Thus, once plants emerged from the surface, the satin-woven structure facilitated the disorientation of the structure and the growth of plants, while the plain-woven structure had less contact with the soil surface because of its higher flexural rigidity than the satin-woven structure. This led to the lower initial vegetation growth during the initial days. The twill-woven structure offered moderate flexural rigidity and a float length that restricted plant growth compared with the satin structure. Thus, in the satin weave, all the 60 seeds germinated within nine days, while 12 days were required for germination in the twill weave. In the plain weave, however, only 55 seeds had germinated by the end of 21 days. In

Figure 6: Germination results after 21 days

Table 6: Germination performance of jute and coir geomeshes

Type of material	Type of weave	Numbers of plants germinated							Total vegetation (%)	Average number of roots	Average length of roots (cm)	Total rooting length (cm)
		Day 3	Day 6	Day 9	Day 12	Day 15	Day 18	Day 21				
Coir	Untreated	48	52	56	60	60	60	60	100	4.5	24	6480
	Plain	0	15	38	40	45	48	49	81.66	5	28	6860
	Twill	0	32	35	44	48	50	52	86.67	5	33	8580
	4 end satin	0	42	43	48	52	54	54	90	4	16	3456
Jute	Untreated	48	60	60	60	60	60	60	100	5	24	7200
	Plain	19	42	44	51	55	55	55	91.67	8	35	15400
	Twill	24	54	58	60	60	60	60	100	6	60	21600
	4 end satin	28	58	60	60	60	60	60	100	4	20	4800

coir geomeshes, germination occurred on the sixth day and started after two days in jute geomeshes. This reason for the difference in the start of germination leas in the fact that jute geomeshes facilitate the faster initial growth of vegetation due to their finer and softer yarns than the coir geomeshes [18].

In jute geomeshes, 100% vegetation was observed at the end of 21 days. When the plain geomesh was applied to the bare surface, the vegetation percentage decreased to 91.67%. However, twill and satin-woven jute geomeshes resulted in the same vegetation percentage as the bare surface at the end of 21 days (Table 6). In coir geomeshes, the vegetation percentage also decreased with a change in the geomesh structure. Plain, twill and satin weaves demonstrated percentages of 81.66%, 86.67% and 90%, respectively. The bare surface demonstrated 100% vegetation because there was no external obstruction for the plants. Amongst all the geomeshes, plain-woven geomeshes demonstrated the highest flexural rigidity, which led to a lower vegetation percentage (Table 1). Jute geomeshes demonstrated a higher vegetation percentage than coir geomeshes in all types of structures. This is because germinating plants were not able to pass through the coir yarns due to the rigid fibres, which offered higher resistance to the plants, while in jute geomeshes, the plants passed through the geomeshes due to its finer and softer yarns. Moreover, different types of weave also affected the number of roots and root length in loamy sand. On the bare surface, an average root length of 24 cm was observed, while root lengths of 35 cm, 60 cm and 20 cm were observed in plain, twill and satin weaves, respectively. It is evident from Table 6 that root length increased when the plain and twill structure of geomesh was used in place of the bare surface, but decreased when a satin-woven structure was used. The satin-woven structure had a longer float length, which increased its contact with the soil. For this reason, the movement of air through the soil was restricted, resulting in a lower root length in the satin-woven structure [14, 25]. The highest number of roots per plant were observed when plain geomesh was applied to the bare surface: five roots per plant were observed on the bare surface while, eight, six and four roots per plant were observed in plain, twill and satin weaves, respectively (Table 5). Coir geomeshes also demonstrated similar trends to jute geomeshes.

Total rooting length was the main criterion that determined the overall germination performance of the geomeshes. In general, in jute geomeshes, the number of plants germinated at the end of 21 days was highest in the satin-woven structure. However, the total rooting length was lowest because of lower number of roots per plant and lower root length. The twill-woven structure demonstrated the longest root length, while the moderate number of roots per plant and moderate vegetation percentage led to a higher total rooting length. For similar reasons, the twill-woven structure demonstrated the highest rooting length.

4 Conclusion

In this study, the performance of structurally modified jute and coir geomeshes was evaluated at different slope angles. It was observed that all factors (slope angle, weave type and type of material) had a significantly effect on runoff erosion control performance. The slope angle contributed most (52.34%) to erosion control, while the type of weave and material type contributed 25.79% and 12.28%, respectively. It is evident from this study that as the slope angle was increased, runoff erosion control decreased. At lower and medium slope angles, the twill-woven coir geomeshes demonstrated better performance, while plain-woven jute geomeshes demonstrated better erosion control at all slope angles. With a change in structure, the flexural rigidity of coir geomeshes decreased, which helped improve erosion control. The twill-woven structure of jute and coir demonstrated the highest vegetation rate at the end of 21 days. The highest root length was also observed in the twill-woven structure. For this reason, the highest rooting length was observed in the twill-woven structure of jute and coir geomeshes. In general, at a lower slope angle, plain- or twill-woven geomeshes can be used, while at a higher slope angle, plain-woven jute geomeshes should be used for better erosion control.

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